6-77-96-0 • 1 JUNE 1967

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AD 660457

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THE EFFECT OF LUNAR GRAVITY ON MAN'S PERFORMANCE OF BASIC MAINTENANCE TASKS

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PUBLICATION REVIEW

This work was conducted with Lockheed Missiles & Space Company's Independent Development funds as part of the Lunar Surface Exploration Simulation Program.

This report has been reviewed and approved.

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FOREWORD

This study was conducted as part of the Lunar Surface Exploration (LUSEX) Simulation Program. This LMSC independent development program has as its major objective the development of a lunar environment simulation test bed for the purpose of establishing man's operational capabilities and limitations in the lunar environment. The major LUSEX simulation components consist of: (1) a one-sixth gravity suspension system utilized in this study, (2) a model of the lunar surface referred to as LUSURF, (3) a man-rated altitude chamber, measuring 18' x 18' x 36', which permits simulation of lunar vacuum conditions, (4) a treadmill for simulating extended lunar walking tasks within the laboratory or chamber setting, and (5) realistic mockups of advanced lunar vehicles and scientific exploration aids. These tools, when utilized with test subjects meeting astronaut qualifications and wearing realistic space suits, permit a high fidelity simulation of lunar EVA mission activities.

In addition to a simulation of the lunar extravehicular environment, the airlock (10' x 10' x 10') associated with the altitude chamber has been configured to represent an early lunar shelter. This simulated shelter, when used in conjunction with the chamber for EVA activities, provides a capability for full-scale, long-duration, mission-simulation studies. The lunar gravity study described in this report is a part-task simulation effort leading to the goal of high-fidelity full-mission simulation.

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ABSTRACT

Nine subjects were trained extensively on three maintenance tasks: bolt torquing, connector mating, and nut threading. They were randomly distributed into one of three clothing conditions (shirt-sleeve, vented suit, and pressurized suit) and trained and tested on all three tasks in three gravity conditions (one gravity, one gravity in the harness, and one-sixth gravity). This study demonstrated that lunar gravity imposed a twenty-five-percent performance decrement over performance in one gravity ($p < .01$). The vented suit imposed a sixty-percent performance decrement ($p < .01$) and the pressurized suit imposed a 150-percent performance decrement ($p < .01$) when compared to performance in the shirt sleeve mode. On the basis of these findings and subjective reports, preliminary human factors design criteria were suggested for lunar gravity performance aids. The need for subsequent research in the areas of mission-specific maintenance tasks and candidate job aids to improve performance in the lunar environment was pointed out.

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SECTION I
INTRODUCTION

Past research, employing a variety of simulation methods, demonstrated that man's behavior in lunar gravity differed considerably from his behavior in the earth's gravity. Hewes and Spady (1964 a, b; 1966) found that man could jump vertically as high as fourteen feet in lunar gravity and perform other ordinary tasks in an extraordinary manner. Roberts (1963) investigated man's walking behavior in lunar gravity which he described as a fast walk in slow motion. Wortz and Prescott (1965, 1966) and Hazard (1965) showed that, during walking, man's metabolic rate decreased in one-sixth gravity when compared to his one gravity rate. Although there has been a comprehensive examination of man's physical and physiological behaviors in lunar gravity, few studies have concerned themselves with man's performance of maintenance tasks. Holmes (1965) studied the effectiveness of a variety of tools on maintenance tasks in various gravity conditions including lunar gravity. Using two subjects for his lunar gravity simulation, he found that performance times increased by eight percent over performance on the earth's gravity. However, due to the paucity of subjects, the large number of tasks under examination, and the lack of statistical treatment, Holmes' findings were considered tentative, at best.

The purpose of the present research was to develop data regarding the effects of lunar gravity and candidate lunar clothing conditions (shirt-sleeves, vented suit, and pressurized suit) on man's performance of three basic maintenance tasks (bolt torquing, connector mating, and nut threading) to serve as guidelines for task analyses, timelines, and performance aid designs. It was hypothesized that performance times in one-sixth gravity would increase over those in one gravity (which would not differ from the one gravity harnessed condition), that performance times would increase with increasingly encumbering clothing requirements, and that the connector mating task would be the least affected by the gravity or clothing condition variables.

SECTION II
PILOT STUDIES

A preliminary study was performed to assess the effects of one-sixth gravity on human performance with respect to routine maintenance tasks. These tasks consisted of (1) Torquing--threading nine bolts into receptacles and torquing the bolts with a torque wrench preset to a value of seventy inch-pounds; (2) Connector mating--engaging and disengaging six electrical connectors of assorted sizes; and (3) Threading--threading nine nuts on protruding bolts of three different sizes.

For comparison purposes, two test subjects performed these activities under the following conditions: (1) Shirt-sleeves at one gravity; (2) Vented space suit (gloves and helmet off) at one gravity; (3) Pressurized space suit (3.7 psi) at one gravity; (4) Pressurized space suit at one gravity and 50,000-foot altitude; and (5) Pressurized suit at one-sixth gravity. The results of this study are depicted in Fig. 1. From this chart it is evident that the influence of the pressurized suit and one-sixth gravity have the largest impact on performance times. It is also evident from this chart that partial gravity does not degrade all tasks to the same degree. For example, the torquing task took 513 percent more time in the one-sixth gravity, pressurized-suit condition

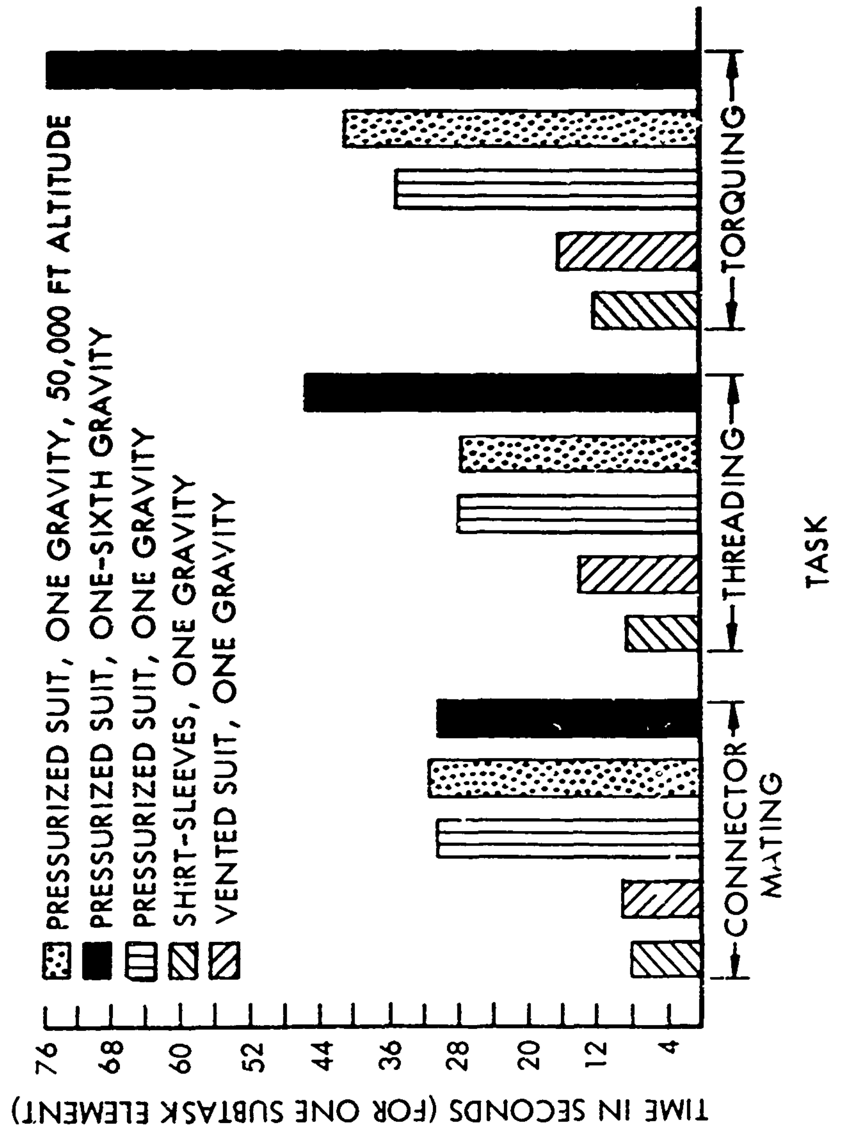

Fig. 1. Comparison of Performance Under Various Gravity, Suited, and Ambient-Pressure Conditions

compared with the baseline shirt-sleeve data. The connector mating task performance was not affected by the one-sixth gravity condition.

The results of the initial study revealed that serious human performance degradations could be anticipated if work space envelopes were not tailored to the peculiar requirements imposed by the lunar environment. It became apparent that such countermeasures as handholds, footholds, and possibly tethers would be required to assist an astronaut in performing tasks which required force applications.

A follow-on pilot study was conducted to determine the value of restraints in counteracting the detrimental effects of one-sixth gravity on task performance. Simple foot restraints and waist tethers were provided to stabilize and anchor the test subject's position relative to the maintenance task fixture. Fig. 2 shows a test subject addressing the experimental task in the restrained mode while suspended by LUNARG and in the pressurized suit. Fig. 3 reveals the beneficial effects of restraints in overcoming the negative attributes of partial gravity. It was felt that, with more sophisticated restraints, performance could be further improved.

Based on these pilot studies, it was apparent that lunar gravity would potentially degrade human performance substantially, even with appropriate restraints. However, test subjects were only given familiarization task training for the pilot studies. The present study was, therefore, con-

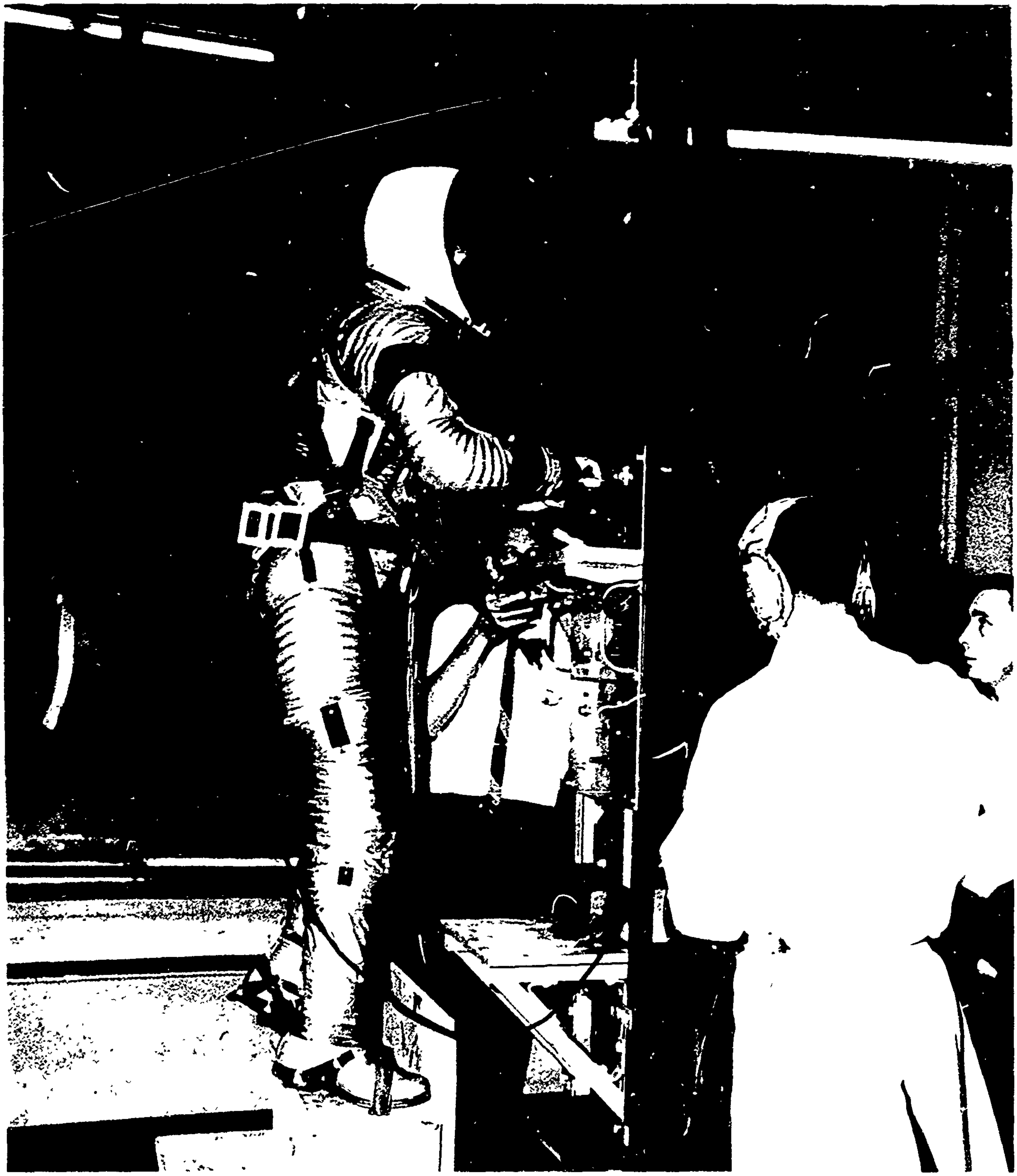

Fig. 2 Performance of Basic Maintenance Tasks in One-Sixth Gravity While Restrained with Tethers and Foot Restraints

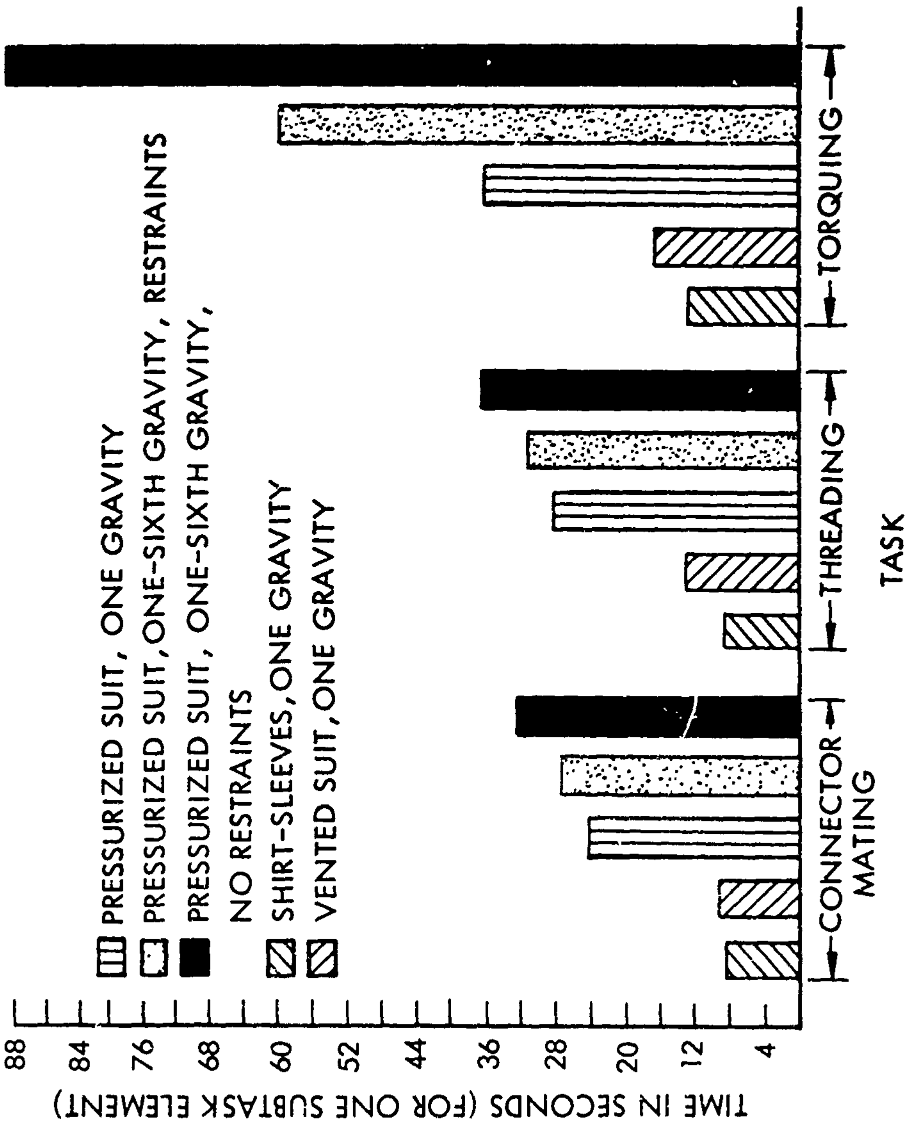

Fig. 3 Effect of Restraints on Performance

cerned with determining the affects of lunar gravity with subjects who had been trained extensively or to peak proficiency.

SECTION III
METHOD

A. Subjects.

Nine male subjects participated in this study. The subjects were selected from a pool of "astronaut" test subjects maintained by Lockheed Missiles & Space Company's (LMSC) Biotechnology Organization. The subjects' ages ranged between twenty-three and thirty-six; all were engineers or physical scientists; all were under six feet in height; and each had performed as a pressure-suited test subject in previous simulation research.

B. Apparatus.

The effect of lunar gravity was achieved by using LMSC's one-sixth gravity simulator, LUNARG (see Fig. 4). This unit, which supports five-sixths of the subject's weight, consisted of nine negator spring motors attached to a cable reeling system. The subject was attached to the aforementioned cable via a harness. Fine balancing of plus or minus one pound accuracy was achieved by placing a skin diver's weight belt around the subject's waist.

Two harnesses were employed in this research. The harness used with the space suit conditions was essentially a parachute-type harness. The subject was picked up, primarily from the crotch, and suspended from a point

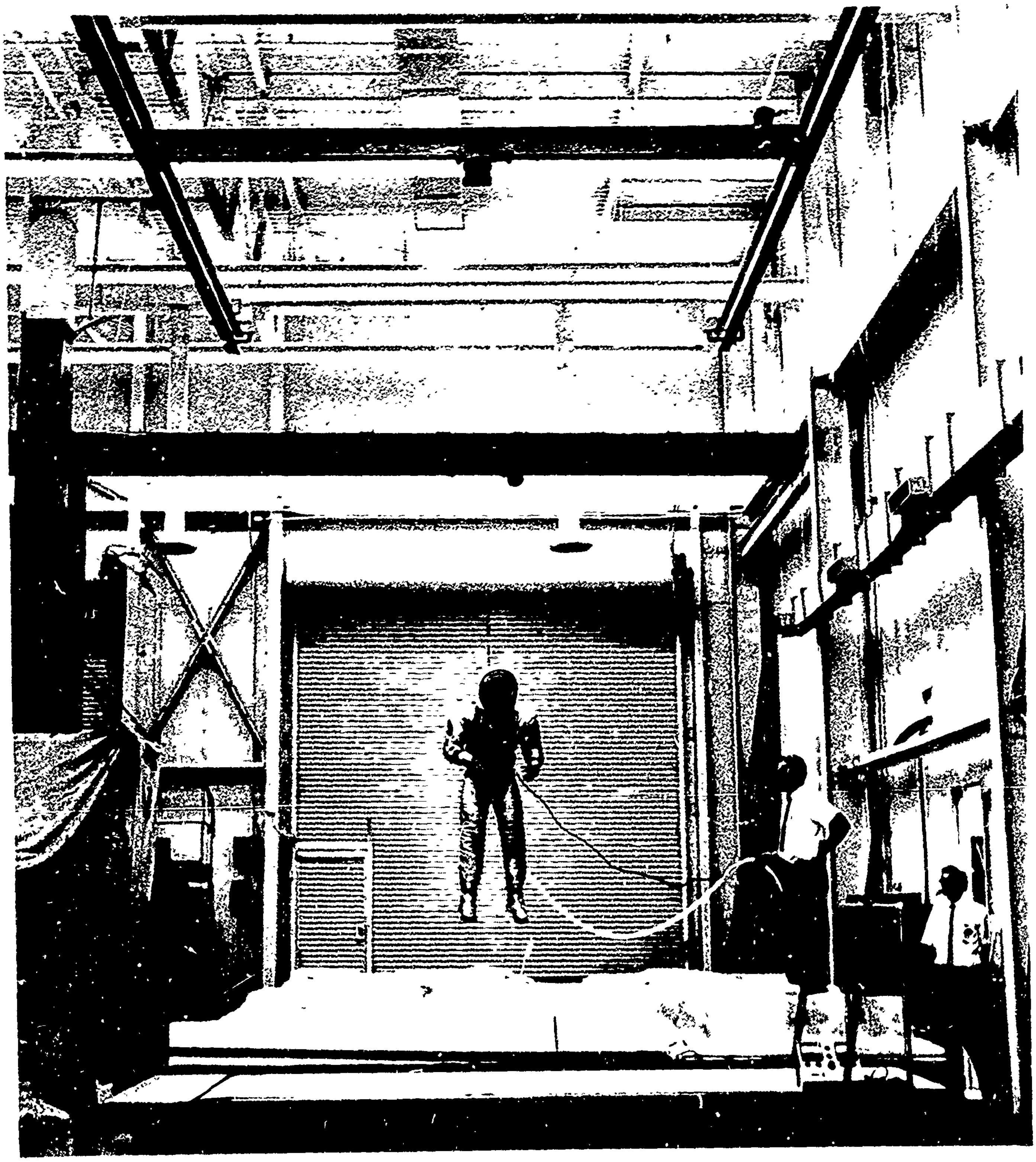

Fig. 4 Lockheed Missiles & Space Company One-Sixth Gravity Simulator (LUNARG)

directly above his center of gravity. The second harness, the "hinie-binder", was a slight modification of the former harness (see Fig. 5). Shorts were added to the parachute-type harness in an attempt to distribute the upward pull of the simulator over the legs, crotch, and hip regions. Both of these harnesses allowed freedom of vertical, horizontal, and yaw movements.

The space suit employed in this study was an Apollo A-4H Training suit, on loan from NASA-Houston. This suit consists of a model C3 helmet, a torso-limb assembly, gloves, and astro-cap.

Since the Apollo A-4H pressure suit had a helmet without a visor, the vented-suit condition was defined as helmet and gloves on with an air ventilization flow of ten cubic feet per minute. The pressurized-suit condition was defined as suit pressurization at 3.7 ± 2 psid with air. The clothing condition referred to as "shirt-sleeve" was defined as street clothing — shoes, socks, slacks, and shirt.

The performance fixture apparatus was a unistrut frame structure 9½ feet in height and 19 inches in width on which a uniform sized panel, 54 inches in height by 19 inches in width by ¼ inch in depth, was placed (Fig. 6). The panel contained three tasks: (1) bolt torquing, (2) connector mating, and (3) nut threading. On the subject's left-hand side of the panel were nine threaded receptacles into which bolts 1 inch long, with a 7/16-inch hexagonal head, were screwed and then torqued down to 70 inch-pounds,

Fig. 5 Shirt-Sleeve Subject in the "Hinie-Binder" Harness

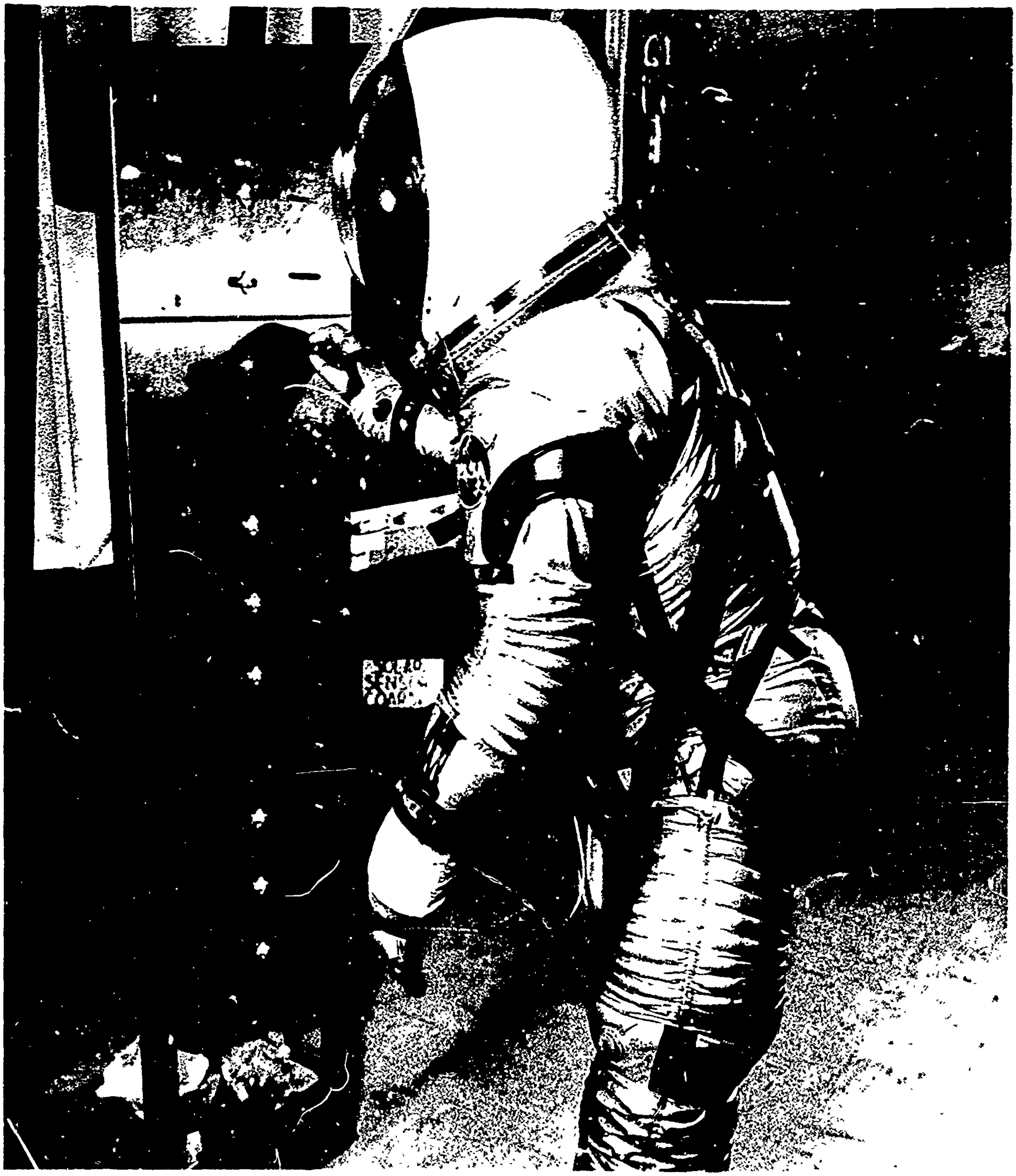

Fig. 6 Pressure-Suited Subject, in One-Sixth-Gravity Parachute-Type Harness, Addressing Performance Panel

using a torque wrench. Nine identical Deutsch push-pull type connectors (½ inch in diameter) were located in the middle of the panel. Twelve equally spaced bolts of three different sizes (¼, 6/16, ½ inch) protruded from the right hand side of the panel. Two of the nuts were hexagonal and fitted on the two larger bolts. The third was a small wing nut. Attached to the performance fixture at a height of 43 inches, and extending out to the right of the panel, was a contents tray (24 x 6½ x 2½). During the experiment, this tray contained the torquing wrench and a predetermined number of each of the task elements.

C. Experimental Design.

The experimental design employed in this research was a partial replication of an eighty-one-cell 3 x 3 x 3 factorial. Nine subjects were randomly assigned to one of three clothing conditions (shirt-sleeve, vented suit, or pressurized suit) with three subjects in each condition. All nine subjects, regardless of clothing condition, performed all three subtasks (torquing, connector mating, and threading) in all three gravity conditions (one gravity, one-gravity harnessed, and one-sixth gravity). In order to minimize the effects of practice, the subjects were tested in the principal condition, gravity, in a counterbalanced order.

All subjects received task orientation and preliminary training in the shirt-sleeve, one-gravity environment. They were then trained and tested in their respective clothing conditions. Three measures were taken in order to describe the subjects' performance. They were (1) time to perform, (2) errors committed, and (3) subjective responses to a questionnaire. Performance times were analyzed by an analysis of variance technique; errors were analyzed using the Friedman Two-Way Analysis of Variance by Ranks. Responses to the questionnaires were cast into frequency distributions for each clothing condition.

D. Procedures.

The experiment was divided into two parts: (1) orientation and preliminary training, and (2) specific training and testing. The former part describes the instructions given to the subjects and the base-line training in the shirt-sleeve one gravity environment. The latter part describes training in specific clothing and gravity conditions and testing.

Orientation and preliminary training. Each subject was given the following instructions at the experiment site:

> "On the performance fixture in front of you are three tasks: bolt torquing, connector mating, and nut threading. You are to complete each of these tasks separately and as quickly and accurately as possible. You are to work from top to bottom and from the torquing task to the connector mating task to the threading task. I will start you on each task by saying, 'On my mark...Mark'. At this time the watch will be started. At the completion of the first task, and each subsequent task, you are to report, 'Task Completed' and step back from the panel. The watch will then be stopped. Errors, such as dropping a bolt, will be recorded during the task also. You may take a rest in between tasks. When you are ready to begin again, indicate such to the experimenter. This procedure will be followed for all three tasks, always working from the torquing task to the connector mating task to the threading task. During the torquing task, all bolts are to be screwed into the panel first, and torqued

> with the torque wrench to the preset value. During the connector mating task, all connectors are to be placed on the board first, and then removed. The nut threading task requires that all nuts be threaded on the bolts first, and then removed. At no time during the test are you allowed to use the unistrut frame structure or the edge of the panel as a hand hold. Are there any questions?"

One exception to this procedure was necessary. During the course of the experiment, it was discovered that the subjects participating in the pressurized suit condition were unable to successfully complete all of the task elements on the performance panel. This was not due to the inability of the subjects to reach all of the task elements since for all subjects regardless of clothing condition the top of the panel was placed one inch above their shirt-sleeve height, but rather to the amount of fatigue and the difficulty of manipulation in the extreme high and low positions. For example, although the subjects were able to place the nine bolts into the panel, they were unable to torque the bolts in the highest and lowest positions with the torque wrench to the preset value of seventy inch-pounds. As a consequence, the work area of the panel was reduced such that the pressure suited subjects were required to complete the middle five torquing and connector mating task elements, and the middle eight threading task elements. Average time to complete one task element was computed for all subjects on all tasks.

At the completion of the instructions, the subjects were given an opportunity to manipulate the three tasks until they were satisfied that they had fully understood the instructions. The subjects were then trained in the shirt-sleeve one-gravity mode until an asymptote in time and errors was reached. This required about one-half to one hour's time.

Specific training and testing. Specific training and testing proceeded first with the shirt-sleeve group, then with the vented-suit group, and lastly with the pressurized-suit group. In all three clothing conditions, subjects were trained to asymptote in time and errors in a particular gravity condition, and then tested immediately afterward. At the completion of a test in a given gravity condition, the subjects moved on to the next gravity condition, as described by the schedule of counterbalanced orders, and were trained to asymptote and then tested. This procedure was carried out for all three gravity conditions. Time to perform each task, time between each task, and errors were recorded during each test. At the completion of the testing, the subjects were asked to fill out questionnaires relating to performance in clothing and gravity conditions and performance of the various tasks.

SECTION IV
RESULTS

The results reported in this section are divided into three parts: baseline training, specific training and test, and questionnaire responses.

A. Baseline training.

Table 1 summarizes the results of baseline training. The mean number of shirt-sleeve, one-gravity training trials to performance asymptote was 8.89 with a standard deviation of 2.31 trials. The mean time to perform one torquing task element at asymptote was 11.37 seconds with a standard deviation of .81 seconds. The mean time to perform one connector mating task element at asymptote was 3.12 seconds with a standard deviation of .25 seconds. The mean time to perform one threading task element at asymptote was 8.53 seconds with a standard deviation of .60 seconds. It is important to remember that the performance times reported refer to mean time to perform one task element, for example, the mean time to torque one bolt, instead of the total time to perform all nine bolt torques. A total of one error was committed by the nine subjects at baseline training asymptote.

B. Specific training and test.

All nine subjects received baseline training in the shirt-sleeve, one-gravity mode. At the completion of this training, the subjects received

TABLE 1

BASELINE TRAINING: SHIRT-SLEEVE ONE GRAVITY

Subject		Task/Time in Seconds for One Task Element		
		Torque	Connect	Thread
1		10.00	3.00	9.50
2		11.61	3.67	8.50
3		10.44	3.00	7.42
4		12.22	2.89	9.08
5		11.89	3.33	8.75
6		10.55	3.11	8.92
7		11.89	2.89	7.83
8		11.67	3.00	8.17
9		12.00	3.22	8.59
	Mean:	11.37	3.12	8.53
	S.D.:	.81	.25	.60

specific training on all tasks in a particular clothing condition and in a given gravity condition. Since the gravity conditions were counterbalanced, individual subjects required different numbers of training trials for different clothing conditions and different gravity sequences. The latter depended on the amount of transfer of training from baseline training. For example, training and test in one gravity had complete transfer to the one-gravity harnessed condition while transfer from one gravity to one-sixth gravity showed much less transfer, depending on preceding specific training and test sequences.

The results of this experiment are summarized in Table 2 and Figure 7 for performance times. In general, there was a significant difference in performance times between the three clothing conditions ($p < .01$). Further analysis of this finding revealed that performance in the vented suit required more time than in the shirt-sleeve mode ($p < .01$). Performance in the pressurized suit required significantly more time than the vented suit ($p < .01$), and, therefore, required significantly more time than the shirt-sleeve condition. In terms of percentage of time increase, the vented suit showed a 63.61% increase over the shirt-sleeve mode. The pressure-suit condition showed a 127.70% increase over the shirt-sleeve condition and a 39.16% increase over the vented suit.

The effect of the three gravity conditions was significant beyond the .01 level of confidence. An analysis of the specific components of this variable revealed no significant difference between the one-gravity condition

TABLE 2

STATISTICAL ANALYSIS OF PERFORMANCE TIMES

Source	Sum of Squares	df	Mean Square	F
Clothing	1,349.31	2	674.65	26.92**
S/Groups	150.34	6	25.06	
Gravity	128.83	2	64.42	26.40**
Task	2,630.99	2	1,315.50	539.14**
Clothing x Gravity	16.64	4	4.16	1.70
Clothing x Task	349.69	4	87.42	35.83**
Gravity x Task	30.21	4	7.55	3.09*
S/Groups x Gravity	41.28	12	3.44	1.41
S/Groups x Task	100.39	12	8.36	3.43**
Clothing x Gravity x Task	19.72	8	2.46	1.01
S/Groups x Gravity x Task	58.57	24	2.44	

*$p < .05$
**$p < .01$

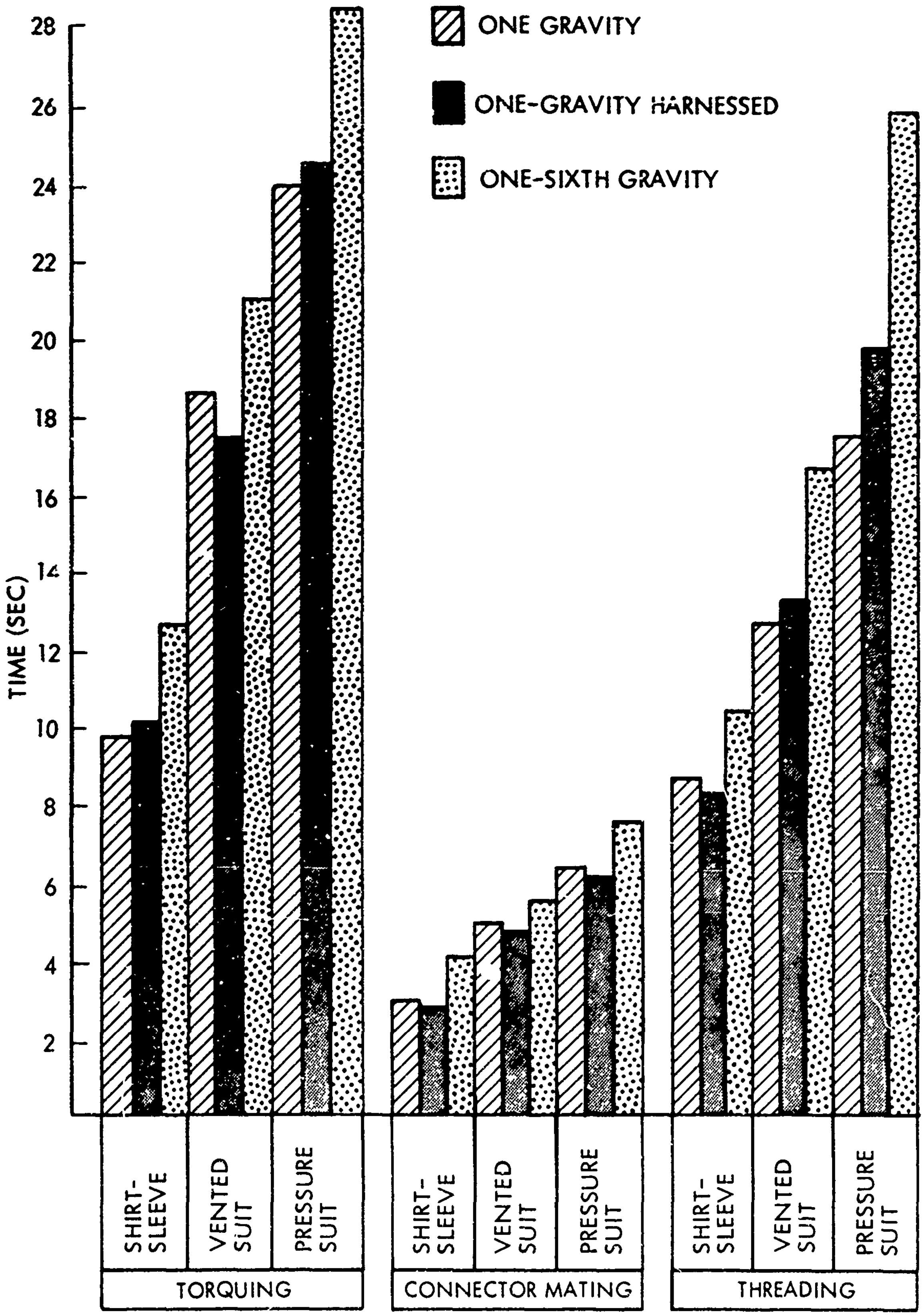

Fig. 7 Performance Times by Task for all Gravity and Clothing Conditions

and the one gravity harnessed condition. However, performance in the one-sixth gravity mode took significantly longer than in the one-gravity harnessed condition ($p < .01$), and significantly longer than in the one-gravity condition. With respect to percentage increase in time, the one-gravity harnessed condition showed a 1.8% increase over one gravity. The one-sixth gravity mode showed an increase in performance time of 23.52% over one gravity, and an increase of 21.33% over the one-gravity harnessed condition.

The difference in performance times for each of the three tasks was significant beyond the .01 level of confidence. Using a one-degree-of-freedom test, it was demonstrated that the threading task took significantly longer than the connector mating task ($p < .01$). Further, it was demonstrated that the torquing task took significantly more time to perform than the threading task ($p < .01$). In terms of percentage of time increase, the threading task showed a 192.24% increase over the connector mating task. The torquing task showed a 267.18% increase over the connector mating and a 25.64% increase over the threading task.

The interaction between clothing and gravity was not significant. This was interpreted to mean that for every level of the gravity condition, performance in the clothing condition remained relatively constant. In short, the one-sixth gravity condition required greater time to perform each of the tasks regardless of clothing condition, and regardless of clothing condition, one gravity and one gravity-harnessed required about the same time to perform.

The interaction between clothing condition and task was significant ($p < .01$). This was interpreted to mean that the difficulty of the tasks did not remain constant for every level of clothing conditions. Specifically, the threading task when in the vented suit showed less of an increase in performance time over the shirt-sleeve condition than did the torquing task in the same clothing mode (56.51% vs. 76.68%). However, a comparison of performance times in the pressurized suit mode revealed that the tasks were approximately equivalent for this condition (130.55% vs. 138.48%). Further, the connector mating task showed much less of a performance time increase in the pressure-suit mode (87.53%) than did either the threading (130.55%) or the torquing (138.48%) tasks.

The interaction between gravity and task was significant ($p < .05$). Again, the difficulty of the tasks did not remain constant for all gravity conditions. This finding is supported by the fact that the threading task in one-sixth gravity took 35% more time to perform than in one gravity.

The interaction between subjects within groups and gravity conditions was not significant. All subjects experienced a decreased efficiency in one-sixth gravity while performing approximately the same in either one gravity or one-gravity harnessed. However, the interaction between subjects and task was significant ($p < .01$). Different tasks were of varying difficulty for each subject within a given clothing condition. Finally, a comparison of the inter-task intervals revealed no differences between task, clothing, or gravity conditions. The mean interval was fifteen seconds.

The term, "error." as employed in this research, referred to the frequency of occurrence of dropping any task element, or holding on to any part of the performance panel or structure framework while performing any of the tasks. There was no attempt made to assign relative weights according to the nature of the error. The Friedman Two-Way Analysis of Variance by Ranks revealed that performance as measured by errors did not differ significantly for any of the three main variables, and there were no significant interactions. These findings were due, in part, to the loose definition of "error."

C. Questionnaire responses.

Subjective impressions of test subjects regarding the tasks under various gravity conditions were examined for conformity with the objective data reported above. All nine subjects agreed that the harness, per se, made no discernable difference. Therefore, the primary differences of concern were between one gravity and one-sixth gravity for the various suited conditions.

In this comparison, a digit enclosed within quotation marks refers to a scale number on a scale from "one" (easy) to "five" (very difficult), and is a mean representation of the three responses.

The subjects were asked to rate the entire maintenance task from easy to very difficult. The shirt-sleeve subjects rated the task as easy in both one and one-sixth gravities, "1" and "1.67," respectively. The vented suit subjects found the task moderately difficult in both gravities– "3" and "3.67." The pressure-suit subjects rated task difficulty as "3" for both gravity conditions.

When asked to identify the most difficult single task, the connector mating task was never indicated. All three shirt-sleeve subjects considered the threading task most difficult in one gravity, and considered the torquing task most difficult in one-sixth gravity. Two vented suit subjects considered the threading task to be the most difficult in one gravity, and all three identified the torquing task as the most difficult when in one-sixth gravity. Torquing and threading were identified as equally difficult by the pressure-suited subjects in both gravities.

In no instance did the subjects identify the middle portion of the performance panel as difficult to work on. Two shirt-sleeve subjects identified the lower portion as the most difficult to work on in both gravities. The higher portion of the panel was identified as the most difficult by all three vented suit subjects. However, two pressure-suit subjects described the lower portion of the panel as the most difficult to work on. In short, it appears that extreme positions, high or low, caused the greatest performance difficulty relative to maintenance task operations.

The shirt-sleeve subjects did not consider the maintenance task fatiguing in either one or one-sixth gravity. Their ratings were "1" and "1.67," respectively. The vented-suit subjects found the task moderately fatiguing, "3," for both gravities. The pressure-suited subjects rated the task as "3" in one gravity and "4" in one-sixth gravity. The indication here is a trend in clothing condition going from the shirt-sleeve to pressure suit mode. It is reasonable to suggest that, if the pressure-suit subjects were required to finish all task elements, they would have reported extreme fatigue.

Subjects in all three clothing conditions unanimously agreed that they felt they had committed the most errors on the threading tasks, irrespective of gravity condition. They also unanimously agreed that they had to change their method of performance of the tasks when in one-sixth gravity as compared to performance in one gravity.

The vented-suit subjects reported that performance dexterity was moderately reduced, "3," when compared to their shirt-sleeve baseline training. The pressure-suit subjects rated suit encumbrance as "5", or extremely restrictive. Finally, no pressure-suit subject reported anxiety in working in the pressurized mode.

SECTION V
DISCUSSION

The purposes of this research were (1) to compare man's performance in earth and lunar gravities, (2) to determine the differential effects of space clothing conditions on performance, (3) to determine the relative difficulty of the three basic maintenance tasks, (4) to provide information for task analysis and timeline studies, and (5) to indicate the nature of preliminary human factors performance aids. Each one of these purposes will be discussed in light of the research findings. The section will be concluded with suggestions for future research.

A. Performance in earth and lunar gravities

The results of this study support the hypothesis that a maintenance task decrement, as measured by time and errors, would be manifested in lunar gravity when compared with performance in the earth's gravity. Performance times in lunar gravity increased significantly over those in one gravity and in one-gravity harnessed conditions ($p < .01$). Although errors in one-sixth gravity increased 340% over errors in one gravity and 159% over errors in one-gravity harnessed, these increases were not statistically significant.

The finding that there was no statistical difference in performance times between one gravity and one-gravity harnessed supported the hypotheses of no differences. It also demonstrated that the differences obtained between lunar and earth gravity conditions were not due to the effect of the harness. The questionnaire responses supported this conclusion. Subjects did not indicate a difference between the one gravity and the one-gravity harnessed modes. However, as new harnesses become available their influence on performance must be ascertained.

The subjects' responses to the questionnaire gave further support to the findings that performance changed in one-sixth gravity as compared to one gravity. According to one subject, "Movements had to be more calculated and precise. Could not push on devices. Found that utilizing arm rotation from elbow forward on threading and torquing produced best results." Another subject summarized the one-sixth gravity effect as, "I stood on tiptoes. More difficult to aim screws or nuts due to less stability. Torquing produced counter torques pushing me away from panel. Takes longer to locomote from tool tray to panel. Easier to bump helmet on panel in one-sixth g."

B. Clothing condition and performance

Perhaps the most significant finding of this research was that subjects performing in the pressurized-suit condition were unable to complete all of the maintenance task elements as originally defined and as completed by both the shirt-sleeve and vented-suit subjects. They indicated that both the high and low portions of the panel were too difficult to reach. As a consequence, the panel work area was redefined, requiring the subjects to perform the middle five-ninths of the torquing and connector mating tasks, and eight-twelfths of the threading task.

The results of the analysis of the performance times supported the hypothesis that the shirt-sleeve clothing condition would impose the least restriction on performance while the pressurized suit would impose the greatest performance restriction ($p < .01$). These findings concurred with Holmes' (1965) description of the pressurized suit mode as being the single most important variable hindering maintenance tool performance. However, it should be noted that the suit used in this study was the Apollo A-4H. There is good reason to believe that performance increases such as those reported in this research would be less with more advanced suits such as the Apollo A-6L space suit or the Litton hard suit.

The results of the questionnaires concur with the performance-time findings for clothing condition. The vented-suit subjects described that condition as moderately restrictive while the pressurized-suit subjects rated the pressure suit condition as highly restrictive. One pressurized suit subject, in response to comparing suit restrictions to shirt-sleeve restriction on a scale from no difference to great difference, circled "great difference," and commented, "Are you kidding?"

C. Maintenance task performance

The findings of this research supported the hypothesis that the connector mating task would take less time to perform than either the threading or the torquing tasks ($p < .01$). The results also supported the finding that the torquing task, due to counter-torques, would take longer to perform than the threading task ($p < .01$). Finally, although the errors analysis did not reveal significant differences between tasks, the results concurred with the hypothesis that the threading task would cause the greatest number of errors. The threading task showed a 477.78% increase in errors over the torquing task and a 420% increase in errors over the connector mating task. The subjects' responses to the questionnaire supported the finding that the greatest number of errors was committed on the threading task. The subjects identified the wing nut as causing the greatest difficulty. Subjectively, the threading task proved to be the most difficult to perform in one gravity whereas, subjectively, the torquing task was identified as the most difficult to perform in one-sixth gravity.

The interactions between task and gravity ($p < .05$), task and clothing ($p < .01$), and task and subjects within groups ($p < .05$) indicated that performance of maintenance tasks were influenced by variables other than the tasks themselves. The task by clothing interaction revealed that the connector mating task was influenced less by clothing condition than either of the two other tasks. Further, the threading task in the vented suit demonstrated a smaller increase in performance time over shirt-sleeves than did the torquing task. However, both threading and torquing were affected to the same extent by the pressurized-suit mode. Again, it was the threading task that proved to be the most sensitive to the gravity variable. Time to perform this task increased sharply in one-sixth gravity. The interaction between subjects within groups and task emphasized the differential capabilities of the subjects relative to a given task. These interactions point out the fact that, in preparing design requirements for lunar maintenance operations, the nature of the task must be considered in relation to the clothing condition under which it will be performed.

D. Task analysis and timeline studies

During the successive stages of design and development of a complex system, information regarding the nature of the human interface with the system in terms of crew functions and tasks is necessary in order to ensure that the system does not impose performance requirements beyond man's capabilities. One purpose of this research was to derive extrapolation figures for maintenance type tasks so that performance time estimates could be made more accurately for lunar maintenance timeline studies.

The performance data, summarized in Fig. 7, provide an empirical basis for assigning performance times to related lunar mission activities. For example, in estimating performance times for lunar intravehicular tasks in shirt-sleeves, a 25.67% increment in performance time should be made over comparable earth based performance. Such generalization from the data obtained in this study would provide a more valid basis for performance time allocations than the "armchair analysis" technique so often utilized.

E. Performance aids

The findings of this research that man's behavior changes under the influence of lunar gravity concurs with the lunar-gravity research literature. The performance decrement observed in lunar gravity and in the various clothing conditions point to the necessity of considering human-engineering design countermeasures for coping with the peculiarities of the lunar partial gravity environment. Although considerable attention is currently being given to performance aids for assisting the astronaut in the zero-gravity environment (Pierson & Geller, 1965), relatively little attention has been devoted to a comparable study of performance aids required to facilitate lunar maintenance and operational tasks (Holmes, 1965). Based on the results of the present research, it may be just as necessary for the astronaut to anchor himself to his task in the lunar environment as it is for earth orbital operations. As one subject stated,

> "Needed one hand for stabilization of position with respect to task. Used right hand to hold on to bolts on left side of panel (threading task bolts) while left hand used for torquing. Handholds would be highly beneficial in accomplishing the task in 1/6 g environment. Ditto footholds."

Based on reports similar to the one cited above, experimenter observation, and performance time and errors, the following represents guidelines for unique design conceptualization of performance aids. Handholds should be provided for the astronaut primarily as a method for obtaining a satisfactory position relative to the task. However, if possible, the astronaut should not be required to use his hands in steadying his position relative to his equipment task since this would limit his ability to use both hands in accomplishing tasks. Further, it appears that a one-hand grip would not be sufficient to steady his position for many tasks. Properly spaced and distributed toe holds and tether anchor points appear to offer promise in helping to steady the astronaut's position for tasks involving force application such as the torquing task. Holmes (1965) investigated tether concepts in lunar gravity for maintenance tool work and concluded that a single tether located from the navel area of the suit to the task was the best candidate. Further research is required. It has also been pointed out that the pressurized suit prohibited performance in extreme positions. In addition to the tethers and handholds just cited, extravehicular work may require lunar ladders or toe holds on the side of structures where work is required above the astronaut's shoulders. Also, work areas extremely close to the lunar surface should be avoided where possible.

Lunar equipment designers should also be concerned with criteria for lunar tools and components. Tools which grip the components may be desirable to reduce time and especially errors. Also, the size of the components, such as nuts and bolts, should be considered. This research agrees with past recommendations (Holmes, 1965) that equipment components and parts should be made large enough for the astronaut to handle with a pressurized glove to minimize errors.

F. Future research

The objective of this research was to develop data regarding the effects of lunar gravity and lunar clothing conditions on man's performance on basic maintenance tasks. From these findings, numerous avenues for research have already been identified. To summarize, lunar maintenance task research should direct itself toward mission specific tasks, updating the findings of the present study whenever possible. Subsequent research should be addressed to optimizing the effectiveness of candidate job aids in overcoming the performance degrading effects attributable to one-sixth gravity. Future research should also be concerned with the criteria for lunar tools and equipment parts.

Future LUSEX studies include a determination of lunar illumination effects on performance and an investigation of the interactive effects of one-sixth gravity, reduced pressure, pressurized suit encumbrances, and astronaut endurance capabilities in the course of performing a full-scale, seven-day, lunar-mission simulation. These studies will be performed utilizing a new LUNARG suspension harness depicted in Fig. 8.

In addition, research efforts beyond the present scope of LUSEX should include a validation study of the various lunar-gravity simulation devices in current use in order to make present and future research findings comparable. Aircraft parabolic flight at one-sixth gravity is suggested as the criterion against which to compare performance in the other simulators to determine the degree of fidelity of each simulation device. The basic maintenance task used in this study could serve as one performance task to be compared across simulators.

Fig. 8 New LUNARG Harness Providing Movement in Pitch, Roll, and Yaw Axes

SECTION VI
SUMMARY

A survey of the literature revealed that man's performance changed when he was placed in simulated lunar gravity. The objective of this research was to derive generalizations about the effects of lunar gravity and proposed lunar clothing conditions on man's performance of basic maintenance tasks. Nine subjects from Lockheed Missiles and Space Company's Biotechnology "astronaut" pool were trained extensively on three tasks: bolt torquing, connector mating, and nut threading. They were then randomly distributed into one of three clothing conditions (shirt-sleeve, vented suit, pressurized suit) and tested on all three tasks in three gravity conditions (one gravity, one gravity in the harness, and one-sixth gravity). Performance measures were time, errors, and subjective report. The results of this research demonstrated that performance times in one-sixth gravity increased significantly over one gravity by about twenty-five percent. It was demonstrated further that the shirt-sleeve clothing condition posed significantly less restriction on performance than did the vented suit which posed significantly less restriction on performance than did the pressurized suit. The torquing task required significantly more time to perform than the other two tasks. An analysis of the frequency of errors failed to show statistically significant performance difference although a substantial percentage increase in errors generally concurred with the performance time findings.

On the basis of these findings, it was concluded that both the lunar gravity and the requisite clothing conditions for the lunar environment significantly decreased man's performance efficiency on basic maintenance tasks. Lunar gravity imposed a twenty-five-percent performance decrement over performance in the earth's gravity. The vented suit imposed a sixty-percent performance decrement and the pressurized suit imposed a 150-percent performance decrement when compared to performance in the shirt-sleeve mode. On the basis of these findings and subjective reports, preliminary human factors design criteria was suggested for lunar gravity performance aids. The need for subsequent research in the areas of mission-specific maintenance tasks and candidate job aids to improve performance in the lunar environment was also indicated.

SECTION VII

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